nucl-th/0506063
LA-UR-05-4415

New broad ^{8}Be nuclear resonances

Philip R. Page*

Theoretical Division, MS B283, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Abstract

Energies, total and partial widths, and reduced width amplitudes of ^{8}Be resonances up to an excitation energy of 26 MeV are extracted from a coupled channel analysis of experimental data. The presence of an extremely broad $J^\pi = 2^+$ "intruder" resonance is confirmed, while a new 1^+ and very broad 4^+ resonance are discovered. A previously known 22 MeV 2^+ resonance is likely resolved into two resonances. The experimental $J^\pi T = 3^{(+)}$? resonance at 22 MeV is determined to be 3^-0, and the experimental 1^-? (at 19 MeV) and 4^-? resonances to be isospin 0.

Keywords: ^{8}Be, resonance, R-matrix

PACS number(s): 27.20.+n 25.10.+s 21.10.Dr 21.10.Hw 21.10.Jx

1 Introduction

What are the properties of the resonances of ^{8}Be? This question is most comprehensively answered by a global analysis of all experimental data based on the best reaction theory available, for example R-matrix theory. Resonance structure tends to be based on single experiments, most recently compiled by TUNL [1]. In contrast, the results of a coupled

*E-mail: prp@lanl.gov

channel R-matrix analysis of data from 69 experimental references are given here. This analysis does not include all experimental data, and hence is not expected to provide the best parameters for all resonances. This is particularly true of narrow resonances (with widths less than 100 keV), which can be approximated by the Breit-Wigner formula. The strength of a coupled channel R-matrix analysis becomes apparent for broad resonances, whose structure can only be determined by analyzing data over a large energy range in various channels, and for which the full force of reaction theory is needed.

The physical content of scattering can be summarized by knowledge of the S-matrix for real energies. However, a more intuitive picture is provided by resonances, which are defined as complex energy poles of the S-matrix. The real part of the pole λ is defined as the excitation energy E_x, and two times the imaginary part as the width Γ. Because these parameters can only be found for complex energies, which cannot be experimentally accessed, resonances involve a mathematical extrapolation beyond observation. Since resonances with small widths tend to have the most pronounced experimental effects, this analysis is limited to resonances fairly near to the real energy axis (the "unphysical sheet closest to the physical sheet" [2]). Even so, controversy centers around very broad resonances which are not observable as clear bumps in experimental cross-sections, particularly a total angular momentum, parity, isospin and excitation energy $J^{\pi}T(E_x) = 2^{+}0(16)$ resonance found in this analysis. This resonance was previously found in an R-matrix analysis by Barker *et al.* [3, 4, 5, 6]. They also found a broad 0^{+} at about 10 MeV. This analysis also discovers a previously unreported broad $4^{+}0(18)$ resonance.

2 Analysis technique

The analysis is performed with the EDA R-matrix code [7]. Integrated cross-section, differential cross-section and polarization data, consisting of more than 4700 points, are fitted with a $\chi^2/(d.o.f.)$ of 7.4 utilizing about 100 free parameters (the R-matrix level eigenenergies and reduced width amplitudes discussed in the next section). This high χ^2 is mostly related to contradictory data, as well as underestimates of experimental relative and normalization errors [8]. Since the resonance structure is insensitive to exclusion of data that fit with more than three standard deviations [8], it is robust under inclusion of the worst fitting data points. Experimental nuclear data on the reactions ${}^4He(\alpha,\alpha_0)$, ${}^4He(\alpha,p_0)$, ${}^4He(\alpha,d_0)$,

$^7Li(p,\alpha_0)$, $^7Li(p,p_0)$, $^7Li(p,n_0)$, $^7Be(n,p_0)$, $^6Li(d,\alpha_0)$, $^6Li(d,p_0)$, $^6Li(d,n_0)$ and $^6Li(d,d_0)$, leading to the ^{8}Be intermediate state, are included. All recoil nuclei are in the ground state. Table 1 contains a complete list of the data in the analysis. Substantial data are entered for the $^4He(\alpha,\alpha_0)$ and $^7Li(p,p_0)$ reactions, and the least data are entered for the $^4He(\alpha,p_0)$, $^4He(\alpha,d_0)$ and $^6Li(d,d_0)$ reactions [8]. The maximum excitation energy above the ^{8}Be ground state is $25-26$ MeV for all reactions except $^4He(\alpha,\alpha_0)$ and $^7Be(n,p_0)$. In the $^4He(\alpha,\alpha_0)$ reaction, data above the maximum α laboratory energy for which data are entered (38.4 MeV) and below the limit of this analysis, are only available as phase shifts [9], and have not been incorporated. For the $^7Be(n,p_0)$ reaction no data above the near-threshold data entered are found below the maximum excitation energy of this analysis. Further details of the data and cross-section fits are available [8, 10].

The excitation energies of the thresholds of the various analyzed channels, with respect to the unstable ^{8}Be ground state, are -0.09 ($\alpha\,^4$He), 17.26 ($p\,^7$Li), 18.90 ($n\,^7$Be) and 22.28 MeV ($d\,^6$Li) [1]. The two-body channels $p\,^7$Li*, $n\,^7$Be* and $d\,^6$Li*, involving resonances less than 100 keV wide, are neglected. These could reasonably be included in an R-matrix analysis. All the channels included are strongly constrained by unitarity (via the R-matrix formalism) and, as explained in the next section, isospin symmetry (charge independence). The channel radii are fixed as follows based on earlier R-matrix analyses: $\alpha\,^4$He (4.0 fm), $p\,^7$Li and $n\,^7$Be (3.0 fm) and $d\,^6$Li (6.5 fm). The fit is insensitive to variation in the $d\,^6$Li radius [8]. The orbital angular momenta included between the two scattered nuclei are: $\alpha\,^4$He (S- , D- , G- , I- and L-waves), $p\,^7$Li and $n\,^7$Be (S- , P- , D- and F-waves) and $d\,^6$Li (S- , P- and D-waves). The inclusion of the highest wave for each channel did not seem to change the qualitative features of the fit, indicating that a sufficient number of waves has been used.

3 Procedure

The Kapur-Peierls expression for the S-matrix at real energies E for channels c' and c is (Eq. 28 of Ref. [11])

$$S_{c'c} = \frac{I_c(a_c,k_c)}{O_c(a_c,k_c)}\delta_{c'c} + i\sum_\mu \frac{\rho_{\mu c'}\rho_{\mu c}}{\mathcal{E}_\mu(E)-E} \qquad \text{where } \rho_{\mu c} = \frac{\sqrt{2k_c a_c}\,\mathcal{G}_{\mu c}(E)}{O_c(a_c,k_c)}. \tag{1}$$

Reaction	Data Reference	E (MeV)	Data Reference	E (MeV)
$^4He(\alpha,\alpha)$	Heydenburg 1956 [12]	$0.6-3.0$	Phillips 1955 [13]	$3.0-5.8$
	Tombrello 1963 [14]	$3.8-11.9$	Steigert 1953 [15]	$12.9-20.4$
	Chien 1974 [16]	$18.0-29.5$	Mather 1951 [17]	20.0
	Nilson 1956 [18]	$12.3-22.9$	Briggs 1953 [19]	$21.8-22.9$
	Bredin 1959 [20]	$23.1-38.4$	Graves 1951 [21]	30.0
$^4He(\alpha,p)$	King 1977 [22]	$39.0-49.5$		
$^4He(\alpha,d)$	King 1977 [22]	$46.7-49.5$		
$^7Li(p,\alpha)$	Spraker 2000 [23]	$0.0-0.1$	Harmon 1989 [24]	$0.0-0.3$
	Rolfs 1986 [25]	$0.0-1.0$	Engstler 1992 [26]	$0.0-1.3$
	Cassagnou 1962 [27]	$1.4-4.8$	Kilian 1969 [28]	$3.4-9.4$
	Freeman 1958 [29]	$1.0-1.5$	Mani 1964 [30]	$3.0-10.1$
$^7Li(p,p)$	Warters 1953 [31]	$0.4-1.4$	Bardolle 1966 [32]	$0.8-2.0$
	Lerner 1969 [33]	1.4	Malmberg 1956 [34]	$1.3-3.0$
	Gleyvod 1965 [35]	$2.5-4.2$	Brown 1973 [36]	$0.7-2.4$
	Bingham 1971 [37]	6.9	Kilian 1969 [28]	$3.1-10.3$
$^7Li(p,n)$	Macklin 1958 [38, 39]	$1.9-3.0$	Barr 1978 [40]	$2.0-3.0$
	Burke 1974 [41]	$1.9-3.0$	Meadows 1972 [42]	$1.9-3.0$
	Elbakr 1972 [43]	$2.2-5.5$	Darden 1961 [44]	$2.0-2.3$
	Austin 1961 [45]	$2.1-3.0$	Elwyn 1961 [46]	$2.0-2.6$
	Baicker 1960 [47]	3.0	Andress 1965 [48]	3.0
	Hardekopf 1971 [49]	3.0	Thornton 1971 [50]	$3.0-5.5$
	Poppe 1976 [51]	$4.3-10.0$		
$^7Be(n,p)$	Koehler 1988 [52]	$0.0-0.0$	Cervena 1989 [53]	0.0
$^6Li(d,\alpha)$	Engstler 1992 [26]	$0.0-1.3$	Golovkov 1981 [54]	$0.1-0.1$
	Elwyn 1977 [55]	$0.1-1.0$	Bertrand 1968 [56]	$0.3-1.0$
	Cai 1985 [57]	$0.5-2.5$	McClenahan 1975 [58]	$0.5-3.4$
	Jeronymo 1962 [59]	$0.9-5.0$	Gould 1975 [60]	$2.2-4.9$
	Risler 1977 [61]	$1.0-5.0$		

Reaction	Data Reference	E (MeV)	Data Reference	E (MeV)
$^6Li(d,p)$	Szabo 1982 [62]	0.1 – 0.2	Body 1979 [63]	0.1 – 0.2
	Bertrand 1968 [56]	0.3 – 1.0	Elwyn 1977 [55]	0.1 – 1.0
	Cai 1985 [57]	0.5 – 2.5	McClenahan 1975 [58]	0.5 – 3.4
	Bruno 1966 [64]	1.0 – 2.0	Gould 1975 [60]	2.3 – 5.0
	Durr 1968 [65]	2.1 – 4.8		
$^6Li(d,n)$	Hirst 1954 [66]	0.1 – 0.3	McClenahan 1975 [58]	0.5 – 2.9
	Szabo 1977 [67]	0.1 – 0.2	Haouat 1985 [68]	0.2 – 1.0
	Elwyn 1977 [55]	0.2 – 0.9	Bochkarev 1994 [69]	0.8
	Thomason 1970 [70]	2.5 – 3.7		
$^6Li(d,d)$	Abramovich 1976 [71]	3.0 – 5.0		

Table 1: Data in the ^8Be analysis. The laboratory energy of the projectile is E.

Here the incoming and outgoing wave functions I and O are functions of E through the wave number k. In principle the S-matrix is independent of the channel radii a. The complex functions $\mathcal{E}_\mu(E)$ and $\mathcal{G}_{\mu c}(E)$ are determined by the R-matrix fit (see below, and also Ref. [11]). Eq. 1 can be extended to complex E, and the S-matrix remains independent of a. The poles of the S-matrix then occurs at complex $E_0 = \mathcal{E}_\mu(E_0)$, where $E_x \equiv Re[E_0]$ is the resonance excitation energy and $\Gamma \equiv -2\,Im[E_0]$ is the resonance total width. The partial width $\Gamma_c \equiv |\rho_{\mu c}|^2 = 2\,|k_{0c}|\,a_c\,|\mathcal{G}_{\mu c}(E_0)/O_c(a_c,k_{0c})|^2$ is evaluated at the pole in terms of the reduced width amplitude $g_c \equiv |\mathcal{G}_{\mu c}(E_0)|$, and is related to the residue at the pole (see Eq. 1). The quantities E_x, Γ and Γ_c are independent of a. Contrary to physical intuition, the sum of Γ_c for kinematically open channels is *not* equal to Γ. It should be cautioned that E_x, Γ and Γ_c all depend on how the extension to complex E is done, and are accordingly quantities that cannot be measured experimentally. However, for narrow resonances where $\mathcal{E}_\mu(E)$ is almost real, E_x, Γ and Γ_c respectively collapse to the usual notions of excitation energy, width and partial width, which can be measured experimentally.

The method of calculation of the S-matrix poles and residues in terms of the R-matrix parameters is briefly summarized from the more complete discussion [2]. To obtain the S-matrix pole positions from the real R-matrix eigenenergies E_λ and the real reduced width amplitudes $\gamma_{\lambda c}$ for the real boundary conditions B_c (fixed in this analysis), as defined in

Ref. [72], a complex energy E_0 is found such that at least one eigenvalue of the complex "energy-level" matrix (p. 294 of Ref. [72]),

$$\mathcal{E}_{\lambda'\lambda} \equiv E_\lambda \delta_{\lambda'\lambda} - \sum_c \gamma_{\lambda' c}[L_c(a_c, k_c) - B_c]\gamma_{\lambda c} \tag{2}$$

is the same as E_0. Here the outgoing-wave logarithmic derivatives L are defined in terms of the outgoing wave functions O in the usual way (Eq. 4.4, p. 271 of Ref. [72]), and are functions of E through the wave number k. The residue at the pole $i\rho_{\mu c'}\rho_{\mu c}$ has already been written in terms of the function $\mathcal{G}_{\mu c}(E_0)$ in Eq. 1. This function can be calculated from the R-matrix parameters by using Eq. 4 of Ref. [2]. Although this function and the energy-level matrix (Eq. 2) are defined for real energies, extension to complex E is done by simply using the functional form of these expressions when working with complex energies. In this way both the S-matrix pole E_0 and the function $\mathcal{G}_{\mu c}(E_0)$, needed to calculate the excitation energy, (partial) width and reduced width amplitude, are defined in terms of the R-matrix parameters.

The EDA code [7] used to perform the R-matrix analysis implements the standard Wigner R-matrix theory [72] without approximations, except for restricting the number of R-matrix levels for a given $J^\pi T$ to a finite number of levels in the energy region of interest. The analysis employs isospin symmetry in the limited sense that isospin constraints on the $\gamma_{\lambda c}$ are implemented as follows. The $\alpha\,^4$He and $d\,^6$Li channels couple to an isospin 0 level, but not to an isospin 1 level. Hence the γ's for an isospin 1 level coupling to these channels are set to zero. Also, a level's γ's for the $p\,^7$Li and $n\,^7$Be channels are related by isospin Clebsch-Gordon coefficients, which are different for isospin 0 and 1 levels.

Let us consider the dissociation of the compound nucleus A into nucleus A' and ejectile a. Define the channel cluster form factor F, proportional to the overlap between the internal wave function of nucleus A and the internal wave functions of the nuclei A' and a, as [73]

$$F(r_{aA'}) \sim \int [\psi_{A'}(\xi_{A'})\psi_a(\xi_a)]^* \psi_A(\xi_A) d\xi_{A'} d\xi_a \, . \tag{3}$$

Here $r_{aA'}$ is the relative coordinate between the C.M. of a and A'. The symbols ξ_A, $\xi_{A'}$ and ξ_a denote internal coordinates of the nuclei A, A' and a, respectively; and ψ are the corresponding internal wave functions. A full definition of F can be found elsewhere (Eq. 7 of Ref. [74]). The integral of $|F|^2$ over $r_{aA'}$ is the widely predicted "spectroscopic factor".

The R-matrix reduced width amplitude $\gamma_{\lambda c}$ for the breakup of a level λ of the nucleus A into A' and a in channel c is defined as [72, 73]

$$\gamma_{\lambda c} = \sqrt{\frac{\hbar^2 a_c}{2M_c}}\, F(a_c) \ , \tag{4}$$

where M_c is the reduced mass for relative motion between A' and a. Comparison between theory calculations and the predictions here are possible by comparing $F(a_c)$ calculated from theory and $\gamma_{\lambda c}$ using Eq. 4. However, this is only possible when the same boundary conditions B_c are imposed at a_c is as standardly done in R-matrix theory. As theory calculations do not usually do this, it is more useful to compare them to $\mathcal{G}_{\mu c}(E)$ in Eq. 1, which is the equivalent of $\gamma_{\lambda c}$ for wave functions with outgoing wave (Kapur-Peierls) boundary conditions (Eq. 30 of Ref. [11]). Hence the R.H.S. of Eq. 4, calculated from theory (usually) for bound states, should be compared to the g_c which will be tabulated in the next section for scattering states.

4 Resonance structure

The E_x, Γ and isospin impurity of the resonances are displayed in Table 2. All J^π are allowed, so that the J^π is independently established by the R-matrix analysis. Isospin 0 and 1 are allowed for all resonances, because these are the only isospins that can couple to the channels in this analysis if isospin symmetry is assumed. The resonances found in Table 2 should be compared to the "experimental" resonances believed to exist on the basis of a summary of resonances found in experimental data and other analyses [1]. A comparison with experiment indicates substantial agreement. Disagreements partially stem from the difference between defining the energy and width from poles of the S-matrix, as is done in the R-matrix analysis, and defining them from Breit-Wigner formulae, as is often the case in experimental analyses. For example, agreement between the energy and width of the well-known narrowest resonances ($J^\pi T(E_x) = 0^+0(0)$, $1^+0(18)$, $1^+1(18)$, $3^+0(19)$ and $3^+1(19)$) is much better than those of the well-known broadest resonances ($2^+0(3)$ and $4^+0(11)$). However, the parameters of the $4^+0(11)$ resonance found from $^4He(\alpha,\alpha)$ alone ($E_x = 11.5(3)$ MeV, $\Gamma = 4000(400)$ keV) [1] are in perfect agreement with this analysis. Since the R-matrix analysis contains more data than any known analysis, the experimental masses and widths may well be in doubt, although this is less likely for narrow experimental resonances.

$J^\pi T$	E_x (MeV)		Γ (keV)		i	
	R-m.	Exp.	R-m.	Exp.	%	
0^+0	[0.01]	0	[0.01]	0.00557(25)	[0]	†‡
	20.13	20.2	750	720(20)	0	†‡
1^+0	18.17	18.150(4)	140	138(6)	1	†‡
1^+1	17.66	17.640(1)	10	10.7(5)	0	†‡
1^+1	20.45	-	690	-	0	†
2^+0	2.77	3.03(1)	1200	1513(15)	[0]	†‡
	16.40	-	19200	-	0	†Ш
	20.10	20.1	680	880(20)	4	†‡
	22.09	22.2	590	≈ 800	0	†‡
	22.78	-	1670	-	0	¶
	23.25	25.2	2000	-	0	†
3^+0	19.24	19.24	170	227(16)	29	†‡
3^+1	19.02	19.07	270	270(20)	30	†‡
4^+0	11.57	11.35(15)	4400	≈ 3500	0	†‡
	17.59	-	7900	-	0	†Ш
	24.35	25.5	4600	broad	0	†
1^-0	19.33	19.4	650	≈ 645	13	
2^-1	18.92	18.91	120	122	2	
3^-0	21.35	21.5	950	1000	0	
4^-0	21.50	20.9	1060	1600(200)	0	

Table 2: Comparison of R-matrix and "experimental" [1] energies E_x and widths Γ of ^{8}Be resonances. Energies are relative to the experimentally determined ^{8}Be ground state. The experimental error is indicated in brackets. The isospin impurity i of the squared amplitude means that $1 - i$ of the resonance is in the isospin T indicated in column 1. Theory calculations: Confirmed (†) or not confirmed (¶) by NCSM [75]. Confirmed (‡) or not confirmed (Ш) by GFMC [76]. Quantities in square brackets are not accurately determined by this analysis. For a discussion of the $1^-1(22)$ resonance see the text.

Except for the two very narrow experimental resonances $2^+(16.6; 16.9)$ that are not considered in the R-matrix fit because no data are entered in their energy region, the following experimental resonances are not found in the analysis: $4^+0(20)$, $(1,2)^-1(24)$, and three resonances in the region $22-23$ MeV with unknown $J^\pi T$ [1]. For the latter three resonances, and $(1,2)^-1(24)$, the reason is that these resonances were observed in reactions other than those analyzed here [1]. Of the reactions studied here, the $4^+0(20)$ resonance is only non-negligibly observed in $^4He(\alpha,\alpha_0)$ [1], and data from the experimental reference [9] are not included here.

The narrow ground state 0^+0 resonance parameters in Table 2 are not an improvement on experiment, since no low-energy $^4He(\alpha,\alpha_0)$ data are included at the same excitation energy as the resonance energy. The experimental $J^\pi T = 1^-?$ at 19 MeV [1], and the $4^-?$ [1], are found to have isospin 0, having allowed for both isospins.

The quantum numbers of the peak at 21.5 MeV in the $^7Li(p,n_0)$ reaction is experimentally thought to be $J = 3$, with the parity possibly positive [1, 38, 77]. Our fits prefers the quantum numbers $J^\pi T = 3^-0$, having allowed for both parity and both isospin possibilities. The new data included [43, 50, 51] hence updates the old experimental parity assignment based on old data [38, 77]. A positive parity assignment of the 21.5 MeV resonance is inconsistent with theory for the following reason. The only kinematically allowed decay channels analysed here are to $p\,^7$Li and $n\,^7$Be. The NCSM predicts that the 3^+0 and 3^+1 resonances above the lowest-energy resonances with the same quantum numbers have weak couplings to $p\,^7$Li and $n\,^7$Be [74]. The same is true for VMC if the $T = 1$ ^{8}Li states are taken as a guide to the $T = 1$ ^{8}Be states [78]. The weak couplings to $p\,^7$Li and $n\,^7$Be are not consistent with the need for the resonance here.

Two resonances with the same quantum numbers are found at $22-23$ MeV in Table 2. The $2^+0(23)$ resonance at 22.78 MeV fits the peak observed around 1 MeV d laboratory energy in the $^6Li(d,\alpha_0)$, $^6Li(d,p_0)$ and $^6Li(d,n_0)$ reactions. On the other hand, the $2^+0(22)$ resonance fits the peak at around 6 MeV p laboratory energy in the $^7Li(p,\alpha_0)$, and around 45 MeV α laboratory energy in the time-inverse $^4He(\alpha,p_0)$ reactions. Although it is conceivable that all these peaks can be fitted with just one 2^+0 resonance, with the $d\,^6Li$ threshold at 22.28 MeV, the current fit clearly prefers two resonances. The lower mass resonance is well established [1]. The existence of the higher mass resonance only became apparent once $^6Li(d,X)$ data above ≈ 1 MeV d laboratory energy were included, and hence does not contradict an analysis [79] of

$^6Li(d,\alpha)$ data below 1 MeV which only found the $2^+0(22)$. The existence of two 2^+ resonances at 21.5 MeV and 22.5 MeV were previously suggested by a qualitative analysis [80] of the $^7Li(p,n_1)$ and $^7Li(p,p_1)$ reactions not analyzed here, in order to explain a broad dip in the n_1 yield at the same energy as a broad bump in the p_1 yield. However, this analysis cannot be regarded as strong evidence for two 2^+0 resonances. It is unclear whether two 2^+0 resonances at $22-23$ MeV is confirmed by NCSM theory calculations [75]. This calculation *does* find an extra 2^+0 state at $14-21$ MeV, which is known as an "intruder" state because it does not appear in the naïve shell model. Whether this intruder should be identified with the $2^+0(23)$ or with the extremely broad $2^+0(16)$, discussed below, is unclear.

The 23.25 MeV resonance found in the R-matrix analysis (Table 2) is denoted by $2^+0(25)$. The reason is that when the peak in $^6Li(d,\alpha_0)$ at a d laboratory energy of ≈ 3.5 MeV is artificially enhanced by substantially decreasing the size of the error bars, the resonance appears at 25.06 MeV, in agreement with experiment, with an unchanged width.

Most of the resonances found in the R-matrix analysis correspond to resonances known experimentally. The exceptions are the extremely broad $2^+0(16)$ and very broad $4^+?(18)$ resonances (as well as the $1^+(20)$ discussed in the next paragraph). The $2^+0(16)$ has previously been reported in an R-matrix analysis of $\alpha\,^4$He elastic scattering, $^9Be(p,d)$ and β-delayed 2α spectra from ^{8}Li and ^{8}B [3, 5, 6] at ≈ 9 MeV [4, 5, 6]. The energy, but not the existence, of this level is dependent on the channel radius used in the R-matrix fit [6, 81]. For example, an analysis of β-delayed 2α spectra from ^{8}Li and ^{8}B together with $\ell = 2$ $\alpha\,^4$He phase shifts finds that 2^+ intruder states below excitation energy 26 MeV need not be introduced [81]. Although the S-matrix (and its poles and residues) are formally independent of the chosen channel radii for infinitely many R-matrix levels, actual analyses employ a finite number of levels, which can lead to different energies for different channel radii. In addition, the energy of 2^+0 varies by several MeV as new data are included, consistent with the expectation that the energy should not be particularly well constrained for a very broad resonance. A NCSM theory calculation finds the 2^+0 and 4^+0 intruders at $14-21$ and $20-26$ MeV respectively [75]. However, a recent GFMC calculation finds no need to introduce extra 2^+ or 4^+ states below respectively 22 and 19 MeV [76]. The disagreement between NCSM and GFMC may be due to the large widths of the intruder states (Table 2), which imply substantial variation in the energies extracted from these calculations which treat all the states as bound. Whether very broad states should be seen in calculations that treat states as bound is debatable.

The current fit has a new $1^+1(20)$ resonance. Although it is not listed in the standard experimental compilation [1], it is interesting to note that theory calculations predict such states: NCSM predicts one 1^+0 resonance and two 1^+1 resonances at $20-22$ MeV [75], and GFMC one 1^+0 at $\approx$ 19 MeV [76]. It is intriguing to note two coincidences between this analysis and theory. (i) The NCSM predicts large couplings of a $\approx$ 20.37 MeV 1^+1 state to $p\,^7$Li and $n\,^7$Be and not to $d\,^6$Li [74]. The robust $1^+1(20)$ resonance seen in this analysis is at $E_x = 20.45$ MeV from Table 2, with strong couplings to $p\,^7$Li and $n\,^7$Be and not to $d\,^6$Li according to Table 3. (ii) Of the three 1^+ resonances predicted at $20-22$ MeV in NCSM, only the $\approx$ 20.37 MeV 1^+1 has large couplings to $p\,^7$Li and $n\,^7$Be, which are the only kinematically open channels for decay, amongst the channels analysed here [74]. The same is true for VMC if the $T=1$ ^{8}Li states are taken as a guide to the $T=1$ ^{8}Be states [78]. This coincides with the finding here that only one new 1^+ state is needed, and that this state has isospin 1.

The 2^- resonance is conceptually complicated because it lies exactly at the $n\,^7$Be threshold, and hence requires sophysticated analysis. Several such analyses have been performed [1], typically yielding a resonance with $E_x = 18.9$ MeV and $\Gamma \approx 100$ keV, although there is disagreement on the width. Most strikingly, an analysis of $^7Li(p, n_0)$ and $^7Be(n, p_0)$ data finds $\Gamma = 1634$ keV [82], based on a prescription whereby the sum of the Γ_c equals Γ. As previously mentioned, this is not the case in our analysis. In contrast, another multi-level R-matrix analysis [52] defines the resonance energy and width as the properties of the pole of the S-matrix, yielding a total width much lower than the sum of the partial widths. This corresponds closely to our conventions, yielding $\Gamma = 122$ keV, $T=0$ and isospin impurity $\approx 24\%$ [52]. This isospin impurity is at odds with $\leq 10\%$ obtained from $^7Li(p,\gamma)^8Be^*(18.9)$ [1]. The current analysis assigns $T=1$ for the 2^- resonance (Table 2). A cautionary note should be mentioned. For all the resonances reported here except the 2^-, the parameters of the pole on the unphysical sheet closest to the physical sheet [2] are quoted in Tables 2-3, as this is thought to be physically most relevant. However, there are poles on other sheets which are physically less relevant. The $2^-0(19)$ is unique in that the resonance is very close to threshold, which blurs the usual prescription for which of the poles are most physically relevant. The parameters of the pole which has an energy exactly at the $n\,^7$Be threshold is displayed in Tables 2-3 because its E_x and Γ correspond most closely to other analyses. There is another nearby pole (on the unphysical sheet closest to the physical sheet) with $E_x = 18.73$ MeV, a much larger width $\Gamma = 640$ keV, $T=1$ and isospin impurity 31%.

$J^\pi T(E_x)$	Γ_c (keV)	$g_c \times 100$ ($\sqrt{\text{MeV}}$)
0^+	$\alpha\,1s$ $p\,3p$ $n\,3p$ $d\,5d$ $d\,1s$	
$0^+0(0)$	[0.010]	[82]
$0^+0(20)$	550 40 120	24 25 53 86 61
1^+	$p\,5p$ $p\,5f$ $p\,3p$ $n\,5p$ $n\,5f$ $n\,3p$ $d\,5d$ $d\,3s$ $d\,3d$	
$1^+0(18)$	81 0.00008 60	91 4 78
$1^+1(18)$	5 0.00008 6	65 27 69
$1^+1(20)$	220 23 160 170 4 80	51 182 44 55 181 38 5 1 4
2^+	$\alpha\,1d$ $p\,5p$ $p\,5f$ $p\,3p$ $p\,3f$ $n\,5p$ $n\,5f$ $n\,3p$ $n\,3f$ $d\,5s$ $d\,5d$ $d\,3d$ $d\,1d$	
$2^+0(3)$	910	100
$2^+0(16)$	1930	170 17 13 54 13 17 14 54 13 10 65 31 11
$2^+0(20)$	170 130 20 130 0.06 140 2 100 0.02	14 43 213 43 11 59 180 50 21 21 25 45 25
$2^+0(22)$	110 240 9 10 7 280 5 10 4	11 42 55 9 46 49 61 10 52 36 68 49 14
$2^+0(23)$	40 290 2 20 0.8 260 2 20 0.3 230 70 30 4	7 45 17 11 13 46 29 13 10 69 35 24 8
$2^+0(25)$	70 930 20 20 4 880 20 30 2 50 40 30 2	9 79 61 10 25 80 79 14 24 29 22 18 5
3^+	$p\,5p$ $p\,5f$ $p\,3f$ $n\,5p$ $n\,5f$ $n\,3f$ $d\,5d$ $d\,3d$	
$3^+0(19)$	130 0.07 0.4 7 0.001 0.009	56 24 57 98 43 131
$3^+1(19)$	320 0.3 2 3 0.0001 0.0004	96 60 157 30 43 82
4^+	$\alpha\,1g$ $p\,5f$ $p\,3f$ $n\,5f$ $n\,3f$ $d\,5d$	
$4^+0(11)$	4000	135 17 28 17 27 0.6
$4^+0(18)$	5300 2 4	135 33 50 33 50 3
$4^+0(24)$	50 40 70 30 60 800	9 60 77 59 77 107
1^-	$p\,5d$ $p\,3s$ $p\,3d$ $n\,5d$ $n\,3s$ $n\,3d$ $d\,5p$ $d\,3p$ $d\,1p$	
$1^-(19)$	44 230 110 4 280 9	101 45 158 101 65 156
2^-	$p\,5s$ $p\,5d$ $p\,3d$ $n\,5s$ $n\,5d$ $n\,3d$ $d\,5p$ $d\,3p$	
$2^-(19)$	3 0.4 73 80 0.03 0.08	5 14 178 58 127 208
3^-	$p\,5d$ $p\,3d$ $n\,5d$ $n\,3d$ $d\,5p$	
$3^-0(21)$	220 340 120 190	96 119 95 120 4
4^-	$p\,5d$ $n\,5d$	
$4^-0(21)$	610 350	153 153

Table 3: The partial widths Γ_c and reduced width amplitudes g_c found in the R-matrix analysis. First, the list of possible channels is indicated for each J^π. Each channel is denoted in the format (reaction) $(2s+1)$ ℓ; where "reaction" is α (α ^{4}He), p (p ^{7}Li), n (n ^{7}Be) or d (d^6Li); and s and ℓ are the spin and orbital angular momentum of the nuclei in the channel. Second, for each resonance, Γ_c and g_c are indicated in the order of the channels enumerated for the corresponding J^π. These entries always start with the first channel, but do not necessarily end with the last channel. For Γ_c this is because the corresponding channels are not kinematically allowed. For g_c the quantities could not be determined because the resonance is too distant from the relevant threshold. Quantities in square brackets are not accurately determined by this analysis. It is understood that Γ_c and g_c are only given for the channels considered in this analysis; and that certain two-body channels, all three-body channels, and higher ℓ, are neglected. The g_c are channel radius dependent, and hence not experimentally measurable.

This pole has the opposite pattern of coupling to the channels: it couples stronger to p ^{7}Li and weaker to n ^{7}Be.

The $1^-1(22)$ resonance has previously only been observed in the $^7Li(p,\gamma_0)$ reaction [1]. This analysis finds a need to introduce this resonance with a strong coupling to p ^{7}Li and n ^{7}Be in the spin 2, D-wave. The parameters of $1^-1(22)$ are not strongly fixed by this analysis and are hence not displayed.

5 Conclusions

The ^{8}Be resonance parameters of most of the resonances up to 26 MeV are determined. The isospins of the 19 MeV $J^\pi = 1^-$ and the 4^- resonances are determined for the first time to be 0. The 21 MeV resonance which was previously assigned to possibly have positive parity is found to be $J^\pi T = 3^-0$. The previously known 22 MeV 2^+0 resonance likely splits into two resonances. A new 1^+1 resonance at 20 MeV is discovered. The resonance parameters enable comparison with GFMC and NCSM theory calculations. Two broad resonances are found, which may not appear in these calculations that treat the states as bound. These resonances

are the extremely broad 2^+0 resonance at 16 MeV, whose existence is confirmed, and a very broad 4^+0 resonance at 18 MeV, which is discovered for the first time. The location of the $T = 1$ resonances is relevant to sorting out the structure of ^{8}Li and ^{8}B. Incorporation of the resonance structure found here in future TUNL evaluations is advocated.

Helpful discussions with G.M. Hale are gratefully acknowledged. The RESP code for the extraction of S-matrix poles was written by G.M. Hale. Some of the data analysed was entered by others, including G.M. Hale and A.S. Johnson [8]. P. Navrátil provided detailed calculations further to Refs. [74, 75]. This research is supported by the Department of Energy under contract W-7405-ENG-36.

References

[1] D.R. Tilley, J.H. Kelley, J.L. Godwin, D.J. Millener, J. Purcell, C.G. Sheu, and H.R. Weller, "Energy Levels of Light Nuclei $A = 8$" (2004), unpublished. This is part of the updated version of F. Ajzenberg-Selove, *Nucl. Phys. A* **490**, 1 (1988).

[2] G.M. Hale, R.E. Brown, and N. Jarmie, *Phys. Rev. Lett.* **59**, 763 (1987).

[3] F.C. Barker, H.J. Hay, and P.B. Treacy, *Aust. J. Phys.* **21**, 239 (1968); F.C. Barker, *ibid.* **22**, 293 (1969); F.C. Barker, G.M. Crawley, P.S. Miller, and W.F. Steele, *ibid.* **29**, 245 (1976).

[4] F.C. Barker, *Aust. J. Phys.* **41**, 743(1988).

[5] F.C. Barker, *Aust. J. Phys.* **42**, 25 (1989).

[6] F.C. Barker, *Phys. Rev. C* **62**, 044607 (2000).

[7] D.C. Dodder, G.M. Hale, and K. Witte, "The Energy Dependent Analysis Code, EDA", unpublished.

[8] P.R. Page, "^{8}Be nuclear data evaluation", Los Alamos preprint LA-UR-04-7172 (2004), pp. 1-35, unpublished.

[9] A.D. Bacher *et al.*, *Phys. Rev. Lett.* **29**, 1331 (1972).

[10] P.R. Page, and G.M. Hale, Proc. of "International Conference on Nuclear Data for Science and Technology" (ND2004), 26 Sept. - 1 Oct. 2004, Santa Fe, NM, p. 390, eds. R.C. Haight *et al.*, AIP conference proceedings Vol. 769 (2005), nucl-th/0410090.

[11] A.M. Lane, and D. Robson, *Phys. Rev.* **151**, 774 (1966).

[12] N.P. Heydenburg, and G.M. Temmer, *Phys. Rev.* **104**, 123 (1956).

[13] G.C. Phillips, J.L. Russell, and C.W. Reich, *Phys. Rev.* **100**, 960 (1955).

[14] T.A. Tombrello, and L.S. Senhouse, *Phys. Rev.* **129**, 2252 (1963).

[15] F.E. Steigert, and M.B. Sampson, *Phys. Rev.* **92**, 660 (1953).

[16] W.S. Chien, and R.E. Brown, *Phys. Rev. C* **10**, 1767 (1974).

[17] K.B. Mather, *Phys. Rev.* **82**, 126 (1951).

[18] R. Nilson, R.O. Kerman, G.R. Briggs, and W. Jentschke, *Phys. Rev.* **104**, 1673 (1956); R. Nilson, W.K. Jentschke, G.R. Briggs, R.O. Kerman and J.N. Snyder, *Phys. Rev.* **109**, 850 (1958).

[19] G.R. Briggs, S. Singer, and W.K. Jentschke, *Phys. Rev.* **91**, 438 (1953).

[20] D.J. Bredin, W.E. Burcham, D. Evans, W.M. Gibson, J.S.C. McKee, D.J. Prowse, J. Rotblat, and J.N. Snyder, *Proc. Roy. Soc. A* (London) **251**, 143 (1959).

[21] E. Graves, *Phys. Rev.* **84**, 1250 (1951).

[22] C.H. King, S.M. Austin, H.H. Rossner, and W.S. Chien, *Phys. Rev. C* **16**, 1712 (1977).

[23] M. Spraker, R.M. Prior, M.A. Godwin, B.J. Rice, E.A. Wulf, J.H. Kelley, D.R. Tilley, and H.R. Welller, *Phys. Rev. C* **61**, 015802 (2000).

[24] J.F. Harmon, *Nucl. Instr. and Meas. B* **40/41**, 507 (1989).

[25] C. Rolfs, and R.W. Kavanagh, *Nucl. Phys. A* **455**, 179 (1986).

[26] S. Engstler, G. Raimann, C. Angulo, U. Greife, C. Rolfs, U. Schroder, E. Somorjai, B. Kirch, and K. Langanke, *Zeit. Phys. A* **342**, 471 (1992).

[27] Y. Cassagnou, J.M.F. Jeronymo, G.S. Mani, A. Sadegli, and P.D. Forsyth, *Nucl. Phys.* **33**, 449 (1962); *erratum ibid.* **41**, 176 (1963).

[28] K. Kilian, G. Clausnitzer, W. Durr, D. Fick, R. Fleischmann, and H.M. Hofmann, *Nucl. Phys. A* **126**, 529 (1969).

[29] J.M. Freeman, R.C. Hanna, and J.H. Montague, *Nucl. Phys.* **5**, 148 (1958).

[30] G.S. Mani, R. Freeman, F. Picard, A. Sadegli, and D. Redon, *Nucl. Phys.* **60**, 588 (1964).

[31] W.D. Warters, W.A. Fowler, and C.C. Lauritsen, *Phys. Rev.* **91**, 917 (1953).

[32] G. Bardolle, J. Cabe, J.F. Chretien, and M. Laurat, *Journal de Physique Colloque C* **1**, 96 (1966).

[33] G.M. Lerner, and J.B. Marion, *Nucl. Instr. and Meas.* **69**, 115 (1969).

[34] P.R. Malmberg, *Phys. Rev.* **101**, 114 (1956).

[35] R. Gleyvod, N.P. Heydenberg, and I.M. Naqib, *Nucl. Phys.* **63**, 650 (1965).

[36] L. Brown, E. Steiner, L.G. Arnold, and R.G. Seyler, *Nucl. Phys. A* **206**, 353 (1973).

[37] H.G. Bingham, A.R. Zander, K.W. Kemper, and N.R. Fletcher, *Nucl. Phys. A* **173**, 265 (1971).

[38] J.H. Gibbons, and R.L. Macklin, *Phys. Rev. D* **114**, 571 (1959).

[39] R.L. Macklin, and J.H. Gibbons, *Phys. Rev.* **109**, 105 (1958).

[40] D.W. Barr, and J.S. Gilmore, Los Alamos Scientific Laboratory Internal Memorandum, December 26 (1978).

[41] C.A. Burke, M.T. Lunnon, and H.W. Lefevre, *Phys. Rev. C* **10**, 1299 (1974).

[42] J.W. Meadows, and D.L. Smith, Argonne National Laboratory Preprint ANL-7938, June 1972.

[43] S.A. Elbakr, I.J. van Heerden, W.J. McDonald, and G.C. Neilson, *Nucl. Instr. and Meas.* **105**, 519 (1972).

[44] S.E. Darden, T.R. Donoghue, and C.A. Kelsey, *Nucl. Phys.* **22**, 439 (1961).

[45] S.M. Austin, S.E. Darden, A. Okazaki, and Z. Wilhemli, *Nucl. Phys.* **22**, 451 (1961).

[46] A.J. Elwyn, and R.O. Lane, *Nucl. Phys.* **31**, 78 (1962).

[47] J.A. Baicker, and K.W. Jones, *Nucl. Phys.* **17**, 424 (1960).

[48] W.D. Andress, R.L. Walter, F.O. Purser, and J.R. Sawers, *Bull. Am. Phys. Soc.* **10**, 440 (1965).

[49] R.A. Hardekopf, C.E. Hollandsworth, R.L. Walter, J.M. Joyce, and G.L. Morgan, *Nucl. Phys. A* **167**, 49 (1971).

[50] S.T. Thornton, C.L. Morris, J.R. Smith, and R.P. Fogel, *Nucl. Phys. A* **169**, 131 (1971).

[51] C.H. Poppe, J.D. Anderson, J.C. Davis, S.M. Grimes, and C. Wong, *Phys. Rev. C* **14**, 438 (1976).

[52] P.E. Koehler, C.D. Bowman, F.J. Steinkruger, D.C. Moody, G.M. Hale, J.W. Starner, S.A. Wender, R.C. Haight, P.W. Lisowski, and W.L. Talbert, *Phys. Rev. C* **37**, 917 (1988).

[53] J. Cervena, V. Havranek, V. Hnatowicz, J. Kvitek, A. Mastalka, and J. Vacik, *Czechoslovak Journal of Physics B* **39**, 1263 (1989).

[54] M.S. Golovkov, V.S. Kulikauskas, V.T. Voronchev, V.M. Krasnopolskij, and V.I. Kukulin, *Sov. J. Nucl. Phys.* **34**, 480 (1981).

[55] A.J. Elwyn, R.E. Holland, C.N. Davids, L. Meyer-Schutzmeister, J.E. Monahan, F.P. Mooring, and W. Ray, *Phys. Rev. C* **16**, 1744 (1977).

[56] F. Bertrand, G. Greiner, and J. Poiret, Centre d'Etudes de Lineil Report No. CEA-R-3428, 1968 (unpublished).

[57] D. Cai, E. Zhou, and C. Jiang, *Priv. Comm.* C. Jiang (1985).

[58] C.R. McClenahan, and R.E. Segel, *Phys. Rev. C* **11**, 370 (1975).

[59] J.M.F. Jeronymo, G.S. Mani, F. Picard, and A. Sadegli, *Nucl. Phys.* **38**, 11 (1962).

[60] C.R. Gould, J.M. Joyce, and J.R. Boyce, Conference on Nuclear Cross-Sections and Technology, Washington, 697 (1975).

[61] R. Risler, W. Grüebler, A.A. Debenham, V. König, P.A. Schmelzbach, and D.O. Boerma, *Nucl. Phys. A* **286**, 115 (1977).

[62] J. Szabo, M. Varnagy, Z.T. Body, and J. Csikai, Conf. on Nuclear Data for Science and Technology, Antwerp, 956 (1982).

[63] Z.T. Body, J. Szabo, and M. Varnagy, *Nucl. Phys. A* **330**, 495 (1979).

[64] G. Bruno, J. DeCharge, A. Perrin, G. Surget, and C. Thibault, *Journal de Physique* **27**, 517 (1966).

[65] W. Durr, G. Clausnitzer, D. Fick, R. Fleischmann, H.M. Hofmann, and K. Kilian, *Nucl. Phys. A* **122**, 153 (1968).

[66] F. Hirst, I. Johnstone, and M.J. Poole, *Philosophical Magazine* **45**, 762 (1954).

[67] J. Szabo, Z.T. Body, S. Szegedi, and M. Varnagy, *Nucl. Phys. A* **289**, 526 (1977).

[68] *Priv. Comm.* Haouat (1985).

[69] O.V. Bochkarev, V.A. Vukolov, E.A. Koltynin, E.A. Kuz'min, Yu.D. Molchanov, L.V. Chulkov, and G.B. Yan'kov, Preprint IAE-5821/2 (1994) [also published as: *Yad. Fyz.* **59**, 1749 (1996)].

[70] R.S. Thomason, G. Spalek, and R.L. Walter, *Nucl. Phys. A* **155**, 659 (1970).

[71] S.N. Abramovich, B.Ja. Guzhovskij, B.M. Dzuba, A.G. Zvenigorodskij, S.V. Trusillo, and G.N. Slepcov, *Izvestiia Rossiiskoi Akademii Nauk Serii Fizika* **40**, 842 (1976) [also published as: *Bulletin of the Academy of Sciences of the USSR, Physical Series* **40**, 129 (1976)].

[72] A.M. Lane, and R.G. Thomas, *Rev. Mod. Phys.* **30**, 257 (1958).

[73] M. Ichimura, A. Arima, E.C. Halbert, and T. Terasawa, *Nucl. Phys. A* **204**, 225 (1973).

[74] P. Navrátil, *Phys. Rev. C* **70**, 054324 (2004).

[75] E. Caurier, P. Navrátil, W.E. Ormand, and J.P. Vary, *Phys. Rev. C* **64**, 051301 (2001); P. Navrátil, *priv. comm.*

[76] S.C. Pieper, R.B. Wiringa, and J. Carlson, *Phys. Rev. C* **70**, 054325 (2004).

[77] R.R. Borchers, and C.H. Poppe, *Phys. Rev.* **129**, 2679 (1963).

[78] R.B. Wiringa, *priv. comm.*

[79] K. Czerski, A. Huke, H. Bucka, P. Heide, G. Ruprecht, and B. Unrau, *Phys. Rev. C* **55**, 1517 (1997).

[80] G. Presser, and R. Bass, *Nucl. Phys. A* **182**, 321 (1972).

[81] E.K. Warburton, *Phys. Rev. C* **33**, 303 (1986).

[82] A. Adahchour, and P. Descouvemont, *J. Phys. G* **29**, 395 (2003).